NASA CR-1996-201378

Ergonomic Evaluations of Microgravity Workstations

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July 1996

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ACRONYMS

ALBERT	Advanced Lower Body Extremities Test
DSO	Detailed Supplemental Objective
EMG	Electromyography
GBX	Glovebox
GPWS	General Purpose Workstation
GRAF	Graphics Research Analysis Facility
HFEL	Human Factors & Ergonomics Laboratory
ISS	International Space Station
LDFR	Long Duration Foot Restraint
STS	Space Transportation System

ACKNOWLEDGMENTS

This research was supported by Contract Number NAS9-18800 from the National Aeronautics and Space Administration and conducted at the Johnson Space Center in Houston, Texas. The authors wish to thank the following people for providing hardware and/or software that was crucial to the KC-135 phase of this experiment: Dr. Carter J. Kerk and Khaled Al-Eisawi of the Human Factors and Ergonomics Group of the Industrial Engineering Department of Texas A&M University for providing force/torque data acquisition hardware and software; Donnie McCaghren of the Experiments and Components Test Branch of the Marshall Space Flight Center for providing the Material Sciences glovebox mockup; Chris Mease of the Space Life Sciences Payload Office at Ames Research Center for providing gauntlets for the General Purpose Workstation.

Thanks are also extended to Lynette Bryan at Krug and Linda Billica and Bob Williams of the Reduced Gravity Office for assistance in preparing for and scheduling the KC-135 flights, as well as to Pete Stanley, Wes McCalip, and Deborah Boles of Imagery Services for their work obtaining and configuring the special cameras required. Cynthia Chmielewski of Lockheed Martin Engineering and Sciences Company is thanked for her support of the electromyography data collection and overall data reduction. Melva Dobbins, Randy Morris, Nathan Moore, Carlos Sampaio, and Janella Youmans also deserve thanks for participating in the KC-135 phase of this research. For the Shuttle phase, the authors wish to thank the crews of STS-73, STS-58, and STS-50 for their participation in our study.

ABSTRACT

Various gloveboxes have been designed for use aboard the Shuttle and International Space Station (ISS). Although the overall technical specifications are similar, the crew interface is unique for each glovebox. In addition, the human factors requirements of gloveboxes for microgravity are not well documented. Therefore, a series of ergonomic evaluations of the various glovebox designs was conducted by the Human Factors and Ergonomics Laboratory (HFEL) at the Johnson Space Center. The overall goal of these experiments was to identify the human factors requirements for a new generation glovebox designs in an attempt to provide commonality across different designs in terms of operator interface.

First two microgravity evaluations were conducted aboard the Shuttle to evaluate the material sciences glovebox (GBX) on STS-50 and to evaluate the General Purpose Workstation (GPWS) on STS-58. Follow-up DSO on STS-73 was manifested to evaluate the modified GBX design in conjunction with a foot restraint system. Finally, a KC-135 evaluation was to conducted to compare combination of two different arm hole interfaces and two different foot restraints (one with knee support and one without).

The KC-135 evaluation generally indicated that flexible arm holes were better than rigid ports for repetitive fine manipulation task to allow maximum range of arm movement. Posture analysis of video from the flights revealed that very similar postures were assumed by both the smallest (female) and tallest (male) subjects at all four workstation/restraint configurations evaluated, possibly suggesting that problematic postures are not necessarily a function of the operator's height but a function of the task characteristics. Although the more confining GBX yielded the highest mean force production across subjects, there is concern that the subjects were using the restrictive nature of the GBX's cuffs as an upper-body restraint in order to achieve such high forces. Such usage of the cuffs has been known to lead to neck/shoulder discomfort during long work shifts. Finally, EMG data revealed more consistent muscle performance at the GBX; the variability in the EMG profiles observed at the GPWS was attributed to the subjects' attempts to provide more stabilization for themselves in the loose, flexible gauntlets.

The STS-73 DSO revealed that the height of the glovebox should be designed for a 95 percentile American male in order to accommodate a neutral working posture. In addition, the foot restraint with the knee support appeared to be beneficial for the glovebox operations. The crew comments offered were to provide two mechanical modes for the foot restraints: loose (for non-egress adjustment) and lock-down (to keep the restraint position fixed and rigid) in order to accommodate a wide range of tasks without egressing the restraint system.

Thus far, this work has led to the development of preliminary design guidelines for gloveboxes and foot restraints. More comprehensive evaluations are planned to be conducted in order to achieve a better understanding of design effects and quantification of their impact on performance.

Ergonomic Evaluations of Microgravity Gloveboxes

1.0 INTRODUCTION

Confined workstations, where the operator has limited visibility and physical access to the work area, may cause prolonged periods of unnatural posture. Especially, if the task is tedious and repetitive or requires static muscle loading, the confined workstations may have significant impact on posture, fatigue level and performance. Glovebox design is a good example of the confined workstation concept. Gloveboxes are widely used in industry, university, government laboratories, as well as in the space environment, and are known to cause postural limitations and visual restrictions. Task performance at gloveboxes is affected by such factors as constrained arm movements, postural limitations, and visual constraints. In addition, human factors guidelines are not well established even though there are numerous guidelines that specify ventilation, seals, and glove attachment (Eastman Kodak, 1983).

Various gloveboxes have been designed for use aboard the Shuttle and International Space Station (ISS). Although the overall technical specifications are similar, the crew interface is unique for each glovebox (e.g., shape and location of glove ports). The designs of these gloveboxes are primarily driven by machine requirements with minimal consideration of the human interface. As of this date, three glovebox designs have been flown on various Spacelab missions: the Material Sciences Glovebox (GBX), the biorack, and the General Purpose Workstation (GPWS). In addition, three different glovebox designs are planned for the ISS: microgravity sciences glovebox, life sciences glovebox and maintenance work area. Each of these glovebox designs reflects different volumetric and task requirements. For example, the GPWS is a multi-functional facility that supports animal experimentation and microscope use within its volume, whereas the GBX, with less than one-quarter the volume of the GPWS, supports crystal growth and other material science experiments.

The human factors requirements of gloveboxes for microgravity are not well documented. Therefore, a series of ergonomic evaluations of the various glovebox designs was conducted by the Human Factors and Ergonomics Laboratory (HFEL) at the Johnson Space Center. The overall goal of these evaluations was to identify the human factors requirements for next generation glovebox designs in an attempt to provide commonality across different designs in terms of operator interface.

2.0 BACKGROUND

Two previous Detailed Supplemental Objectives (DSOs) have been performed aboard the Shuttle to investigate human factors issues in glovebox design.

2.1 STS-50 Detailed Supplemental Objective 904

The DSO 904 is reserved for human factors assessments onboard Shuttle missions. During Space Transportation System Mission 50 (STS-50), the Spacelab Materials Science Glovebox (GBX) was targeted for a human factors assessment, in which both crew questionnaire data and objective postural data from video downlinks were collected. A crewmember often worked full shifts at this small workstation, performing repetitive tasks. The rigid, iris-designed glove ports tighten around any size arm, causing them to fit extremely tightly.

The seven crewmembers performed various scientific experiments using the GBX. Subjective operator ratings described the glovebox as "not acceptable." It was, "...too small for moving around, hand positioning, and mounting the experiment hardware," and it was reported that the viewing window would have been more efficient if it were larger and slanted forward slightly (Whitmore, McKay, and Mount, 1994, p. 390).

The crewmembers also reported neck and shoulder pain. From the video analysis, approximately 40% of the total observed time, crewmembers assumed a "hunched" shoulder posture accompanied by a severely flexed neck. The crewmembers were unable to maintain an optimal posture which would have reduced the discomfort ratings and the percent of time spent in awkward postures. In addition, computer modeling evaluations were completed by the Graphics Research Analysis Facility (GRAF) within the Flight Crew Support Division at JSC, using a three-dimensional (3-D) interactive graphics system, PLAID. These evaluations revealed that three factors may have resulted in unnatural and uncomfortable posture: (1) design and location of the cuffs, (2) relative location of the viewing window, and (3) task requirement (e.g., eyes required to be close to the task). (Whitmore, McKay, and Mount, 1994, p. 391). This glovebox evaluation helped identify human factors guidelines and issues for optimizing GBX design as it applies to not only the Shuttle Spacelab but also to future spacecraft.

2.2 STS-58 Detailed Supplemental Objective 904

Later, during STS-58, a similar DSO investigated human factors issues in the design of the General Purpose Workstation (GPWS), a multi-functional facility accommodating two operators (Whitmore and Mount, 1995). Its primary use has been to support biological experiments involving animals such as chemical fixation and dissections, in addition to microscope manipulation and in-flight maintenance (Dalton, Jahns and Hogan, 1992; Dalton, Schmidt and Savage, 1992; Wagner, 1983). The GPWS is a larger workstation than the GBX, and its gauntlet interface is much more flexible than the snug glove ports of the GBX. The gauntlets have less of a tendency to restrain the user from performing natural upper body movements. As on STS-50, crewmembers completed questionnaires, and postural analysis was again performed on video downlink from the mission.

The greater freedom of movement allowed by the GPWS is evident in the results of the DSO. No neck/shoulder discomfort was reported by any of the crewmembers, and all aspects of the GPWS design were rated “acceptable.” However, one problem was encountered, the crew reported that, “reaching for loose items was difficult at times due to the interior volume being too crowded” (Whitmore and Mount, 1995). This finding was confirmed with the results of the follow-up human modeling evaluations conducted in the GRAF (Pandya and Hancock, 1995). It was found that a 5th percentile Japanese female could not reach all corners of the work area, regardless of how crowded the interior may be. And even a 95th percentile American male, “needed to squat in order to reach all the corners since the work surface was too low for his stature” (Whitmore and Mount, 1995).

Even though the crewmembers worked in a hunched shoulder posture 47% of the time, no neck/shoulder discomfort was reported. This posture may have been due to both the low, fixed GPWS surface height and the operator’s need to monitor the task in close-up view. The lack of discomfort reporting contrasted with the findings of the GBX DSO, where one crewmember did indeed experience neck/shoulder discomfort during the mission. The difference in the findings of the two studies may be attributed to the difference in the glove port interface; the Spacelab GBX had a rigid cuff design, while the GPWS had flexible gauntlets. The operators were able to move their arms more freely when using the flexible gauntlets. It was decided that additional testing would be required to investigate other possible causes of these differences.

In order to further investigate the reasons for the different findings in the Shuttle experiments, the HFEL’s most recent experimental work has branched out in two different directions. First, an ergonomic evaluation conducted onboard the KC-135, NASA’s reduced gravity aircraft, served as a pilot study. Subsequent to this pilot study, another DSO 904 was manifested onboard STS-73 to further investigate the GBX and the effect of a new foot restraint.

3.0 KC-135 EVALUATIONS

Based on the previous findings of the Shuttle experiments, it was concluded that the crew assumed similar postures at both glovebox workstations, but the high physical discomfort level was only experienced at one of these gloveboxes. This difference was anticipated to be due to the crew interface design (i.e., flexible versus rigid arm holes). Therefore, a pilot test was conducted onboard the KC-135 in order to evaluate the gloveboxes (GBX with rigid cuffs and GPWS with flexible gauntlets) with two foot restraint systems, one with additional knee support. In addition, various performance measures such as maximum force/torque and electromyography were selected to investigate the impact of different glovebox/restraint configurations.

3.1 Approach

The tests were conducted during two flights, each with 40 weightless periods of 20 seconds each. Two workstation/foot restraint configurations were simultaneously evaluated to take maximum advantage of the short microgravity segment of the flights. The primary foci of these evaluations, in prioritized order, were:

1) Postural differences for small and large subjects at different gloveboxes
2) Effects of different glovebox/foot restraint system on maximum voluntary force/torque (Glovebox: rigid versus flexible arm holes; Foot restraints: Advanced Lower Body Extremities Restraint Test (ALBERT) with knee support and Long Duration Foot Restraint (LDFR))
3) Effect of different glovebox designs on shoulder muscle activity (EMG)

The expected results were as follows: taller subjects would assume a more hunched posture; the ALBERT and the GBX would both provide more support and therefore force and torque would be highest at this configuration; the highest muscle fatigue would be observed at the GBX due to its rigid cuffs.

3.1.1 Subjects

Three female and three male non-crew subjects, ranging in height from approximately 5 ft (152.0 cm) to 6 ft (182.4 cm) participated in the study. These subjects were selected based on their wide range of body sizes, as well as their previous KC-135 experience. It should be noted that the KC-135 subjects are required to have a U.S. Air Force Class III physical exam and complete physiological training. A summary of their anthropometric measurements is given in Appendix A, and flight experience is presented in Table 1. Two subjects (one female and one male) flew both flight days.

TABLE 1. Summary of Subject Backgrounds

Information	Responses
Number of subjects	6
Gender	3 females; 3 males
Participants with KC-135 experience	5 out of 6 (3 males; 2 females)

3.1.2 Equipment

3.1.2.1 Workstations

Two different workstation designs were evaluated: the GBX and the GPWS (See Figure 1). Table 2 compares and contrasts the two workstations.

SEE ORIGINAL DOCUMENT FOR GRAPHICS

Figure 1. Workstation mockups onboard the KC-135.

The GPWS interior is accessed via flexible gauntlets attached to the workstation with Velcro. These gauntlets reach to the wrist to allow the use of surgical gloves. The interior volume is considerably large when compared to the GBX. The GBX also has a much more rigid arm hole, or cuff, consisting of taut irises that close around the forearm. Figure 1 shows the experimental setup of this evaluation onboard the KC-135, which closely resembled workstation setup onboard previous Shuttle missions.

TABLE 2. Comparison of the GPWS and the GBX

Workstation Characteristic	GBX	GPWS
Ports	• Taut irises that close around the mid-forearm; surgical-style gloves are worn.	• Flexible gauntlets that reach the wrists; surgical-style gloves are worn.
Interior volume	• 0.883 ft^3 (0.025 m^3)	• 8.5 ft^3 (0.241 m^3)
Viewing areas	• Window on the GBX ceiling	• Large windows on front and one side
Work surface height from the floor	• 3.48 ft (1.06 m)	• 2.67 ft (0.813 m)

3.1.2.2 Foot Restraints

Two restraints were evaluated in conjunction with the gloveboxes: the Advanced Lower Body Extremities Restraint Test (ALBERT), flown on various Shuttle missions, and the Long Duration Foot Restraint (LDFR), designed for use onboard the ISS. In Figure 1 above, the ALBERT is set up at the GBX, and the LDFR is mounted at the GPWS. Table 3 compares and contrasts the two restraints. The version of ALBERT flown onboard the KC-135 was not Class I flight hardware and was slightly less rigid than the actual flight unit.

TABLE 3. Comparison of the ALBERT and the LDFR

Restraint Characteristic	ALBERT	LDFR
Joints (Contact points)	• 2 joints - at operator's knees and feet	• 1 joint at operator's feet
Adjustability	• Height of entire restraint from floor • Angle of foot portions with respect to the floor • Number of adjustment points: 3 • Distance between foot portions	• Height of entire restraint from floor • Angle of restraint with respect to the floor • Number of adjustment points: 4 • Distance between foot loops
	• Distance of knee joint away from the rack surface • Distance between foot and knee portions • Angle of foot portions with respect to the knee portion	• Width of foot loop strap
Foot interface	• Foot slips in-between two cushioned bars that support the instep when foot is fully inserted.	• Foot straps on foot plates.

3.1.2.3 Load Cell and Force/Moment Data Acquisition System

In order to collect sustained force and torque application data across workstation / restraint configurations, a PY6-2001 load cell data acquisition system was utilized (see Appendix B for a hardware sketch). The load cell is a three-inch cube that measures forces (F) and moments (M) in three dimensions, allowing for a total of six data channels. A two-inch diameter knurled knob was mounted on the front surface of the load cell. Figure 2 shows a sketch of the load cell / knob setup, and figure 3 shows a subject performing a knob task inflight. Two data channels were utilized in this experiment: F_z for the Push / Pull task and M_z for the clockwise rotation task. AcqKnowledge® III software was used for both in-flight hand data acquisition and for postflight calculations on the data: averages, standard deviations, maximums, and minimums over any range of each trial.

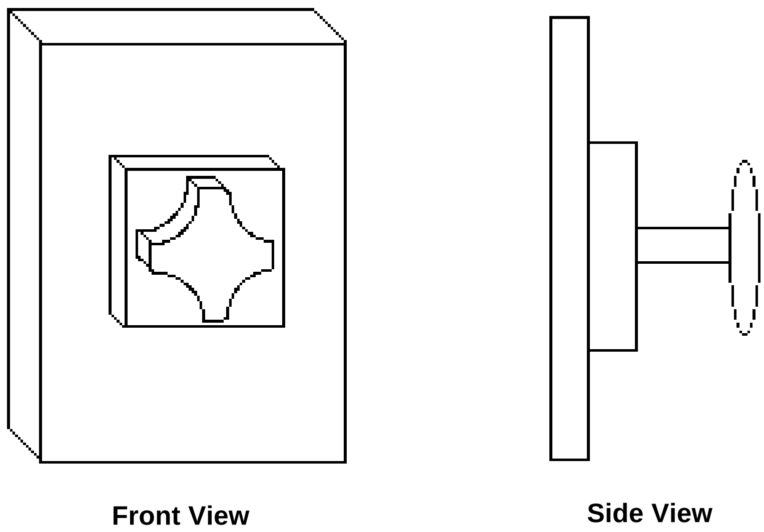

Figure 2. Load cell/knurled knob hardware setup.

SEE ORIGINAL DOCUMENT FOR GRAPHICS

Figure 3. Subject performing the load cell task inflight.

3.1.2.4 Electromyography (EMG)

An ME 3000 Muscle Tester was used to collect muscle electrical activity data. The ME 3000 is a portable apparatus which can operate as an independent data collection device and functions as a collection and recording unit with independent storage capability. The full system also included a computer interface and EMG software. By means of surface electrodes, this device measured electrical activity from different muscles simultaneously. Postflight analysis of the data yields an EMG fatigue analysis for each trial. Digital data were recorded in the memory of the ambulatory device using state-of-the-art amplification technology. The data was then transferred, via the optical interface, to a computer for postflight processing. The amplifiers were connected directly to the ground electrode. This effectively eliminated disturbances caused by movement. Due to the unavailability of the most current technology, with larger memory cards, data was only collected on selected subjects.

3.1.2.5 Video Collection

The Vision 3000 system was used to perform posture analysis of the glovebox tasks that have been recorded on videotape. This system measures the angular and linear dimensions of the postures shown on the videotape by means of capturing and analyzing selected video frames. It works with standard 8mm video equipment and a computer. The posture analysis module of this system was used to examine neck, shoulder, and knee angles at different workstation/restraint configurations.

3.1.2.6 Subjective Questionnaire

A 28-item questionnaire was administered to the subjects postflight (see Appendix C). Subjects rated such items as the glove port interfaces and restraint comfort levels. The questionnaire also gave all subjects an opportunity to voice other comments about the experiment and the equipment.

3.1.3 Procedure

Two tasks were performed onboard the KC-135: a force/torque task and an fine manipulation assembly task. Prior to KC-135 flights, the subjects' anthropometric data, including heights and body segment lengths and circumferences (see Appendix A), were collected. In addition, baseline ground data for the force/torque task were collected under nominal laboratory conditions -- at an open workbench, in a standing position. The subjects were briefed on the experimental protocol onboard the KC-135 before take-off. Once in level flight, the equipment was prepared, and final adjustments were completed. The evaluations were conducted at each workstation simultaneously; while the force/torque task was performed at one workstation, the assembly task was performed at the other. The tasks were then switched in order to collect a complete data set. One or two parabolas were reserved for foot restraint adjustments for each subject. When the restraint adjustments were completed, 6-7 parabolas were scheduled for the force/torque task and 4-5 parabolas for the assembly task. The data were collected only during the microgravity portion of the flights. Upon landing, the subjects were asked to complete the questionnaire and report their comments on the experiment and the workstation/restraint configurations. Detailed descriptions of the tasks are given in the following section.

3.1.3.1 Force/Torque Task

Subjects were asked to perform three force/torque tasks in counterbalanced order. Push, pull, and clockwise rotation tasks were performed with the right hand only. Each task was performed one or two times per flight in random order. The task plate with the load cell was positioned perpendicular to the forearm in order to provide neutral wrist posture for the subject. During each microgravity parabola, the subject was asked to maintain maximum exertion for ten seconds while performing a push or a pull ($\pm F_z$) or a clockwise rotation ($+M_z$) of the knob. For the first two flight days, data was collected at the GBX. During the second flight, the load cell system was moved to the GPWS in order to collect force and torque data at that workstation.

Force and torque data were saved in a format that would allow for the desired postflight analyses (Appendix B). The data were saved in analog format, showing the increase in exerted force, the duration of maximum exertion, and the decrease from maximum for each trial.

A full-body side view of subjects at each workstation was recorded on videotape for postflight postural analysis with the Vision 3000 system. Based on the results of previous research, the analysis concentrated on the neck, shoulder, and knee joint angles in the saggital plane; these joints have been found to define an operator's working posture at a confined workstation in microgravity. An average of 35 frames were captured per microgravity parabola and used for the analysis. Angles for each frame were then averaged over each parabola so that the mean posture for each subject for each parabola (e.g., each workstation / restraint configuration) could be compared.

Surface electromyography (EMG) was used for data collection. One electrode was placed on the right pectoralis for arm extension (push / pull task) and the second electrode was placed on the right posterior deltoid for horizontal adduction of the arm (rotation task). Figure 4 shows where these muscles are located in the upper arm and shoulder area. These electrode placements were selected due to the nature of the shoulder movements to be performed during the test. The shoulder movements in this study (pull, push, and rotate) heavily utilize these two muscles; they are therefore the most appropriate for an EMG fatigue analysis during workstation operations.

During data collection, the sampling frequency was set at 1000 samples per second. Once the EMG data was collected, it was downloaded postflight from the EMG unit to the computer via an optical link. The data was then stored into the appropriate files for analysis, which included: median frequencies, mean power frequencies, and average electromyography for both the posterior deltoid and pectoralis.

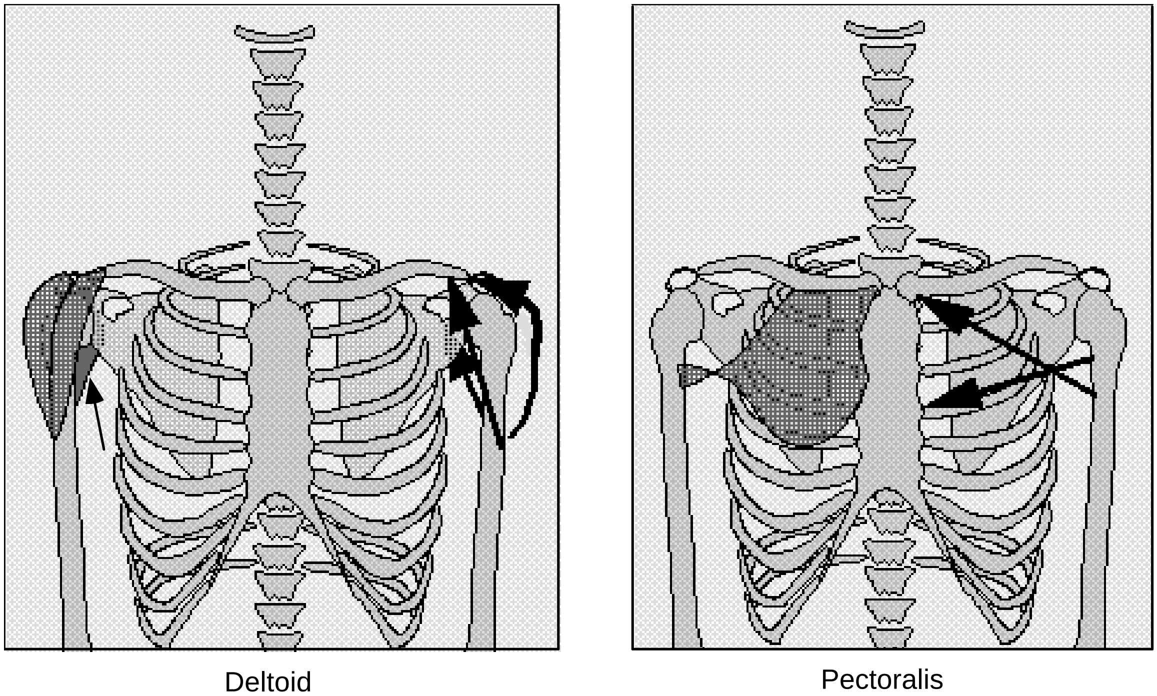

Figure 4. Muscles Selected for EMG. NOTE: The small arrow on the far left points specifically to the Posterior Deltoid.

3.1.3.2 Assembly Task

The load cell task quantitatively evaluated sustained force / torque application. In contrast, the assembly task qualitatively evaluated fine motor skill in microgravity. Subjects were briefed pre-flight on what they would be assembling, and specific directions were posted either inside the glovebox or directly above it for easy in-flight reference. A copy of the subjects' instructions is found in Appendix D.

Items from an erector set were placed in labeled bags; the task required multiple manipulations of these items. The challenge here was to take out the desired pieces without letting the rest float out of the bag into the glovebox. As pieces were obtained from each bag, the subjects placed them in bags labeled with their names. The subjects then assembled these pieces as instructed pre-flight and put their assemblies in their personal bags. Velcro and magnets were provided inside both gloveboxes as temporary restraints for both the bags and the individual erector set items.

Once again, the full-body side view video was used to obtain neck, shoulder, and knee joint angles with the Vision 3000 system. Analysis was identical to that described above for the force / torque task.

Progress on each attempt at the task was recorded, and each subject's bag was checked after each flight. Close-up video of the glovebox interiors was also recorded and used to confirm each subject's progress.

3.1.4 Experimental Design and Constraints

Table 4 below outlines the force / torque and assembly task data collected for each subject. It should be noted that posture data and questionnaire responses were collected from all subjects. The force / torque task was the primary task of this series of KC-135 flights, therefore most parabolas were devoted to it. Subjects 1 and 2, the smallest and tallest subjects respectively, have complete force / torque data sets at all four workstation / restraint configuration. The EMG data was only collected for the force / torque task on a limited number of subjects. The rest of the subjects were scheduled across different configurations so that maximum utilization of hardware and microgravity time was achieved.

TABLE 4. Subject Participation in the Force / Torque and Assembly Tasks

	FORCE/TORQUE TASK								ASSEMBLY TASK			
	with EMG				without EMG				1	2	3	4
Subject #	1	2	3	4	1	2	3	4				
S1 (Female)	√		√		√	√	√	√			√	
S2 (Male)	√	√	√	√							√	
S3 (Female)		√			√						√	
S4 (Male)					√	√					√	
S5 (Male)									√		√	
S6 (Female)									√		√	

1 = GBX/LDFR; 2 = GBX/ALBERT; 3 = GPWS/LDFR; 4 = GPWS/ALBERT

Since the assembly task was secondary, subjects participated in this portion of the study as time and hardware availability allowed. Therefore, less time was devoted to the assembly task, and less data was collected. Furthermore, the objective of having an assembly task was to evaluate performance changes between two workstations of very different volumes. Investigation of the effect of foot restraint on a fine motor task will be left open for later evaluations, because it was expected that workstation design, rather than foot restraint design, would have the more significant effect on task performance in this case.

Since the sample size was very small, and no data set was entirely complete, inferential statistics were not used. Only descriptive statistics such as mean and standard deviation were used in the analysis.

3.2 Results and Conclusions

The primary questions that were addressed in this pilot study, in prioritized order, are as follows:

What is the effect of different glovebox / foot restraint configurations on:

1) posture of small and large subjects?
2) maximum voluntary force / torque?
3) shoulder muscle activity (EMG) data?

These results, as related to each of the above questions, will be discussed separately in the following sections.

3.2.1 Postural Changes

As stated earlier, the Vision 3000 system was used to determine the angular dimensions of three joints: neck, shoulder, and knee. Ideal joint angles were obtained from the neutral body posture in microgravity (Appendix E). Figure 5 shows the posture for the smallest and tallest subjects in this experiment. It is most interesting that they both display the same posture patterns across the four workstation / restraint configurations, with only one exception.

The one exception to the similarities seen in the posture patterns of the two subjects is at the GBX / ALBERT configuration; the tall male's shoulder angle is greater and the neck angle smaller than those of the small female. The large stature difference between these two subjects is most likely the cause. It appeared that when using ALBERT, the tall subject moved further away from the GBX to give himself some space in which to work. By doing so, he reduced the load on the neck and compensated by increasing the shoulder angle. This subject put himself in as ideal a posture as he could at the GBX. The other interesting observation was that the angular variation in the knee joint was slightly greater for the tall subject than the short subject most of the time. The exception was found with the GBX / ALBERT configuration, possibly due to the severe "squat" posture of the female subject.

It is indeed surprising that both subjects, with statures of 59.4 in (151.0 cm) and 72.3 in (183.7 cm), showed such similarities in posture. This finding supports the notion that any posture problems inherent in these workstation / restraint combinations are independent of operator size. One benefit of such a finding is that operators of all statures may be trained to use the same countermeasures to improve poor posture at these workstation / restraint configurations by proper adjustment of restraints and proper orientation of their bodies.

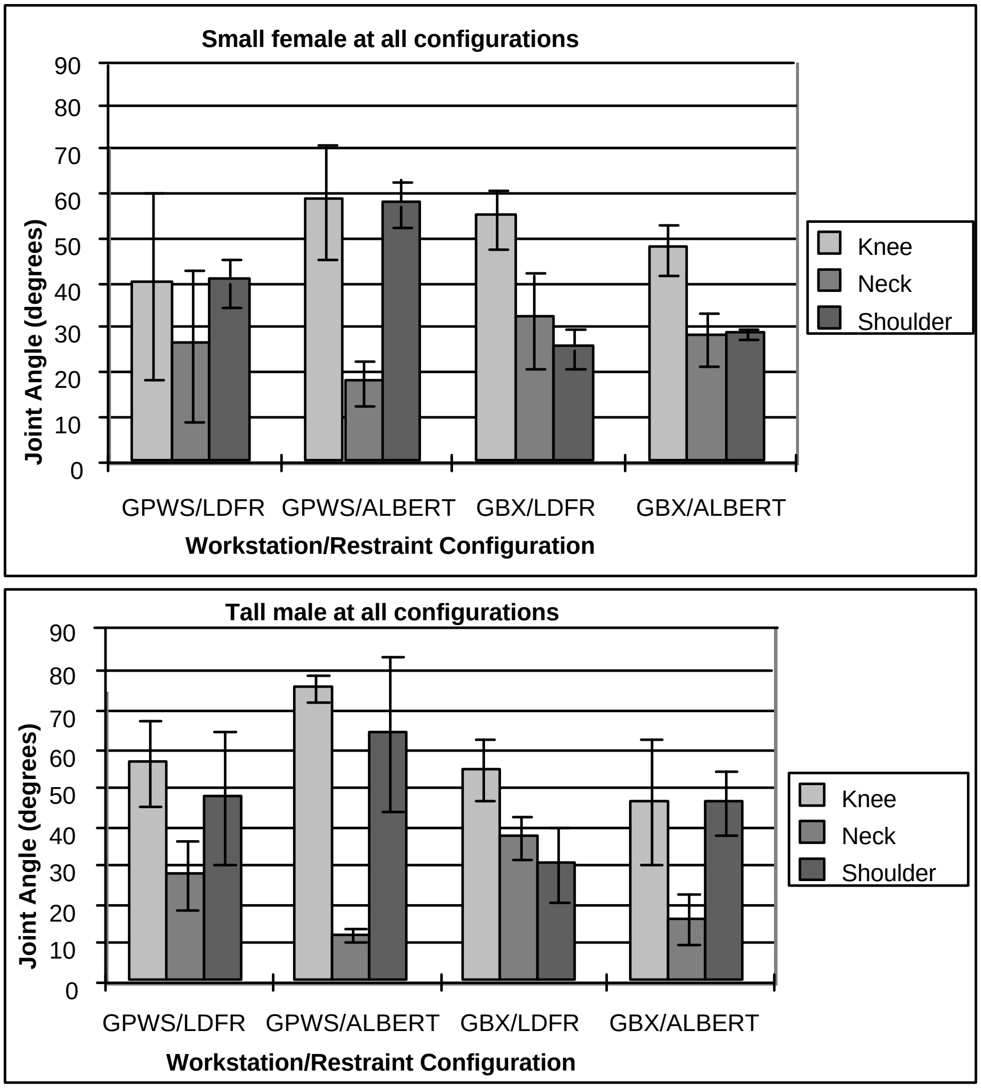

Figure 5. Mean postures for a short female and tall male subject at all workstation/restraint configurations. NOTE: Vertical bars denote one standard deviation above and below the mean.

Since such similarities were observed between the subjects representing the two stature extremes, posture data was collapsed across all subjects to investigate the general trends (Figure 6). GPWS/ALBERT was found to have the lowest neck angle and the highest shoulder angle of all four configurations. This result stems from the fact that ALBERT was mounted on the floor at the GPWS, and, therefore, height adjustment was limited. The lack of height adjustment may have been compensated by greater shoulder angles; smaller subjects needed to raise their shoulders quite high to perform tasks at the GPWS using ALBERT.

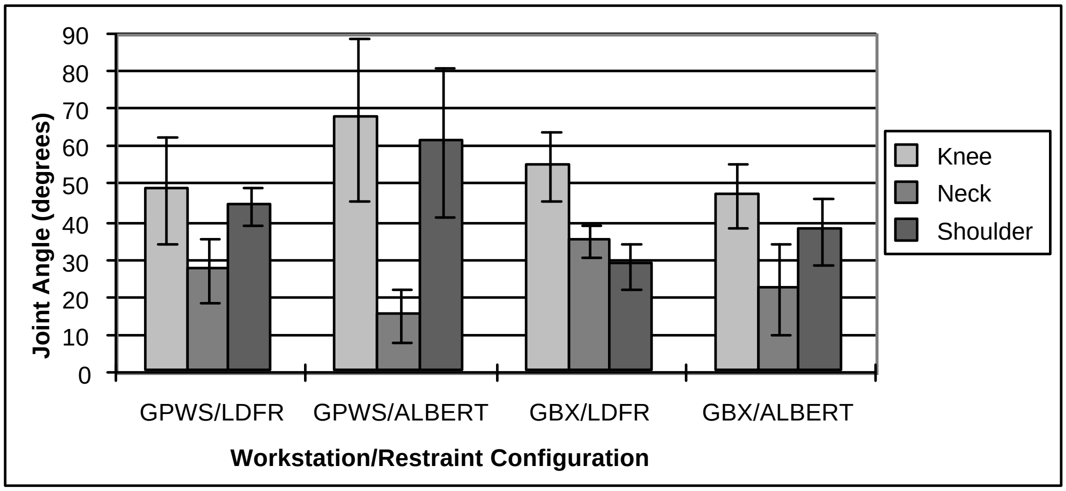

Figure 6. Mean joint angle for each joint (N=4).

A tradeoff may be observed at all workstation / restraint configurations between neck and shoulder angles. When the shoulder angle is highest (GPWS / ALBERT), the neck angle is lowest. As the neck angle increases from this minimum, the shoulder angle decreases at the GPWS / LDFR and at the GBX / ALBERT. Then, at the GBX / LDFR, the tradeoff reverses, and the neck angle is greater than the shoulder angle. The subjects were always compensating for a large angle in one joint by working to reduce the angle in the other in order to maintain an overall posture that was as ideal as conditions would allow.

3.2.2 Force and Torque

The three tasks performed with the load cell were a 10-second push, pull, or rotation. Figure 7 shows the mean forces imparted by all subjects at all conditions. The greatest push force ($+F_x$) is seen at the GBX / ALBERT configuration. With a workstation as confining as the GBX, ALBERT seemed to increase the subject's ability to push, possibly because it provided a cushioned support behind the knee to lean on and to push against while imparting the push force. In microgravity, a push force pushes the operator from the GBX; his or her knees then push against ALBERT. ALBERT keeps the operator from floating away from the GBX and appears to help him / her maintain force over time.

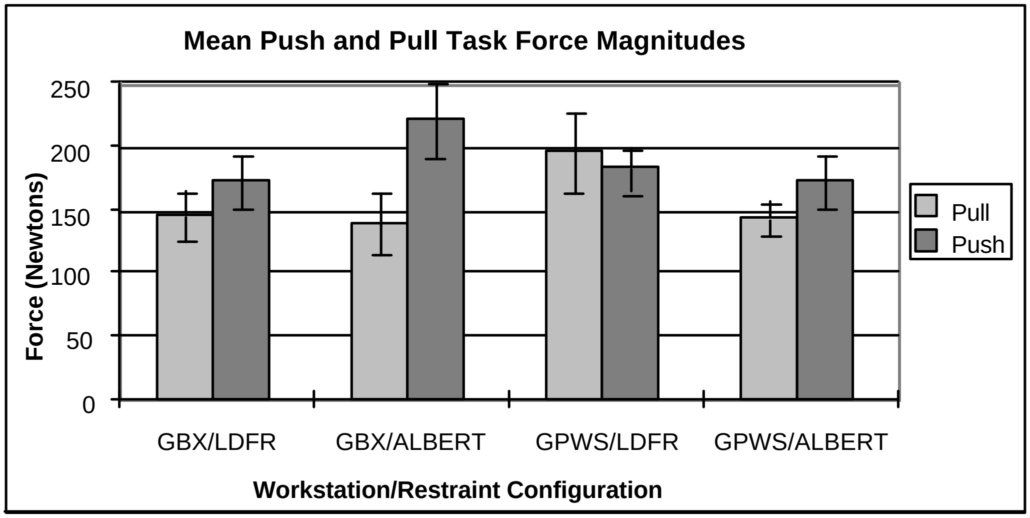

Figure 7. Mean forces imparted by all subjects at all workstation / restraint configurations.

Also, the rigid cuffs of the GBX may have actually helped the subjects impart a higher push force. However, this aid is probably the result of the operator using these cuffs as a restraint, which has been proven to be a bad idea over long periods of time. Past crewmembers have reported shoulder discomfort that was partially attributed to using the rigid cuffs as a restraint device.

The push force at the GPWS / ALBERT is slightly less than that at the GPWS / LDFR. In addition, the push forces seen here were also less than the one observed at the GBX / ALBERT. There are two possible explanations: 1) the flexible gauntlets did not provide any support around the arms to aid in the push task and 2) as stated earlier, the floor-mounted ALBERT configuration at the GPWS limited its range of adjustment, which may have in turn affected the subjects' ability to impart a maximum push force.

For the pull task ($+F_x$), it is interesting to note that the lowest pull force for all four workstation / restraint configurations is seen at the GBX / ALBERT, where the highest push force was observed. The rigid cuffs may have hindered the subjects' performance in this case, and as opposed to the push task, ALBERT provides no lower body support while pulling.

Torques at the GBX using both restraints are less than those at the GPWS (Figure 8). This result was expected; the rigid cuffs of the GBX negatively affected the subjects' ability to rotate the forearm effectively. Even though the range of adjustment for ALBERT was greater at the GBX than at the GPWS, and, therefore, ideal adjustments were made for each subject, the freer movements allowed by the GPWS gauntlets facilitated a small increase in torque magnitudes.

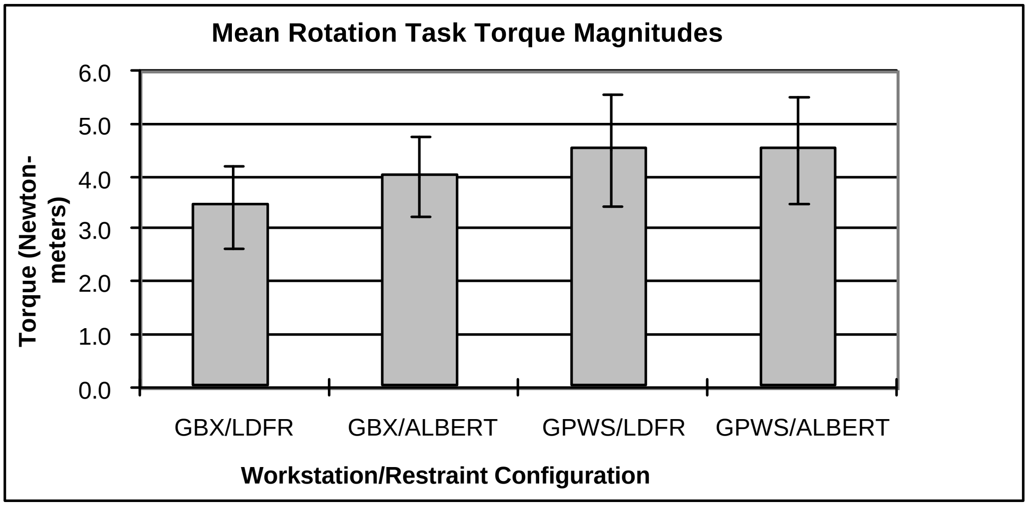

Figure 8. Mean torque imparted by all subjects at all workstation/restraint configurations.

Overall, the differences seen between the LDFR and the ALBERT at the GPWS are not as noticeable for the push and the rotation tasks as they are for the two restraints at the GBX. The more restrictive design of the GBX appears to have magnified the effects of the restraint systems on the magnitude of the forces and torques imparted to the load cell.

3.2.3 EMG

As stated in Section 3.1.4, the EMG data was planned to be collected for two muscles for three subjects (two short female and one tall male subject): (1) Pectoralis for arm extension during the push/pull task, and (2) Posterior deltoid for horizontal adduction of the arm during the torque (rotation) task. For one of the two female subjects, the EMG data was collected only at the GBX/ALBERT configuration due to a hardware setup problem. Even though a complete data set of the male subject was collected, part of the data was inconclusive due to high inconsistency within and between trials and across activities at both workstations. Therefore, the only data analyzed in depth was the EMG data of the second female subject. Data was collected on this subject at the GBX and GPWS using the LDFR (see Appendix F). Table 5 summarizes the Mean Power Frequency (MPF) and the associated force/torque production of this subject in each configuration tested. Fatigue was measured as a drop in MPF on the muscle contraction profiles of Appendix F.

For the pull task, only a low level of fatigue in the pectoralis muscle was observed at the GBX (i.e., mostly consistent MPF over the 12-second trial period). GPWS showed more fatigue than GBX. It appears that the subject had higher pull force value at the GPWS, but it cost her more muscle fatigue.

TABLE 5. Mean Power Frequency (MPF) and Force / Torque Values for the Female Subject (S1)

	Mean Power Frequency (Hz)		Force (N)	Torque (N-m)
	Posterior Deltoid	Pectoralis		
Pull Task				
GBX/LDFR	62.1	72.8	78.56	-
GPWS/LDFR	62.6	71.1	85.67	-
Push Task				
GBX/LDFR	61.6	66.6	79.23	-
GPWS/LDFR	72.5	73.3	86.48	-
Rotate Task				
GBX/LDFR	61.4	92.0	-	3.00
GPWS/LDFR	67.9	67.6	-	2.82

More fatigue and higher MPF values were observed for the pectoralis than for the posterior deltoid during the pull task at both of the workstations. This finding was expected, since the pectoralis was the primary muscle for that task.

For the push task, GBX showed more consistency in MPFs over muscle contraction. GPWS showed a higher level of fatigue and also higher MPFs in both muscles. It was noted that the push force was also higher at the GPWS. It is anticipated that the inconsistency of the muscle performance (i.e., variation observed in MPF over the muscle contraction) may be due to a lack of stability at the flexible gauntlets. Yet at the same time, the flexible gauntlets facilitated a higher MPF and higher push performance.

For the torque (rotation) task, GBX showed more consistency (i.e. less fatigue in the deltoid across muscle contraction than GPWS did). However, the GBX had lower MPF values. It appeared that the rigid cuffs of GBX prohibited excessive arm adduction during the rotation task. Keeping in mind that the posterior deltoid was the primary muscle for this task, it is interesting to note that higher variation was observed in MPF over the muscle contraction both for GBX and GPWS for the pectoralis - implying that there may be inadvertent arm extension movement during the rotation task. This finding needs to be further investigated.

In addition, a drop in MPF was observed at the GPWS with the deltoid for push and rotate from 10 seconds on. This fatigue observation may be attributed to having to stabilize oneself at the GPWS since the flexible gauntlets provided a wider range of movement. This would indeed cause more fatigue toward the end of the trial as observed in the data. The higher MPF may be attributed to the additional muscle effort required to perform the task and simultaneously be attempting stabilization of the body.

Overall, the subject's MPF across trials for the GBX demonstrated a very consistent profile with a minimal level of fatigue, although the push / pull force production was lower at this workstation. It appears that the rigid arm holes may be preferred over the flexible arm holes for the tasks requiring force application. However, it should be noted that only one subject's data was analyzed. Therefore, further investigation needs to be conducted to confirm this finding.

Another interesting finding was that the rotation task appears to be a good short-duration task to investigate muscle activity, because it appeared to cause the most consistent muscle fatigue within a 12-13 second trial. The largest difference between MPF at the GBX and GPWS was observed with the rotation task as well. This finding was attributed to the fact that orientation of the pull / push tasks were perpendicular to the glove port plane (i.e., the arm holes did not impact the task performance), whereas the rotation task movement was on the same plane as the arm holes which may have limited free arm movement and resulted in fatigue over the muscle contraction. Rotation task also yielded the most consistent data. Only one rotation profile (the push task with the pectoralis at the GPWS / LDFR) did not show fatigue at the end of the trial (Appendix F). Push / pull tasks did not show such consistent fatigue at the end of the trials. Therefore, it was concluded that the rotation may be a task where 10 seconds is adequate time to show fatigue.

3.2.4 Assembly Task

On the last day, two subjects performed the task at both workstations with the LDFR. As mentioned in the Procedure section, the effect of workstation design on a fine motor task was investigated. A drastic decrease in performance was seen between the GPWS and the GBX. No subject was able to complete the entire task (see Appendix D for a complete task description), but of the subjects who worked at both workstations, slight task progress was observed at the GBX. One subject did some assembly work in the GBX but far less than in the GPWS. Another subject was only able to collect the necessary parts in the GBX and did not do any assembly work. These subjects spent six to seven parabolas at each workstation.

The volume difference between the GPWS and the GBX had a major impact on the ability to perform this task. Six baggies held the erector set pieces to be assembled. These bags alone took up most of the volume in the GBX, but it was expected that there would be enough remaining volume with which to perform the task. However, it was a challenge for the subjects both to find space in which to assemble the pieces and to sort through the bags for the correct one for each step of the task. Although the remaining volume was deemed sufficient on the ground, the difficulty in finding temporary stowage space and the large number of items free-floating in the GBX greatly impacted performance in microgravity. This dilemma is representative of what crewmembers experience working in the material sciences glovebox in-flight.

3.2.5 Questionnaires

A postflight questionnaire (Appendix C) was administered to all subjects after completing the experiment. Mean responses grouped by category are shown below in Figure 9. Seven represented Completely Acceptable (of the design items), 4 represented Borderline, and 1 represented Completely Unacceptable. The differences seen between the two workstations and the two restraints are barely noticeable. The GBX received only slightly better ratings in all categories: overall design, interior volume, and the glove port interface. For the two restraints, the ALBERT rated extremely high on comfort level, and the LDFR rated only barely higher than ALBERT on overall restraint design. This overall design finding may be due to the fact that there were some minor hardware problems with ALBERT on the final flight and that the ALBERT mockup used in this study is not as sturdy as the actual flight unit.

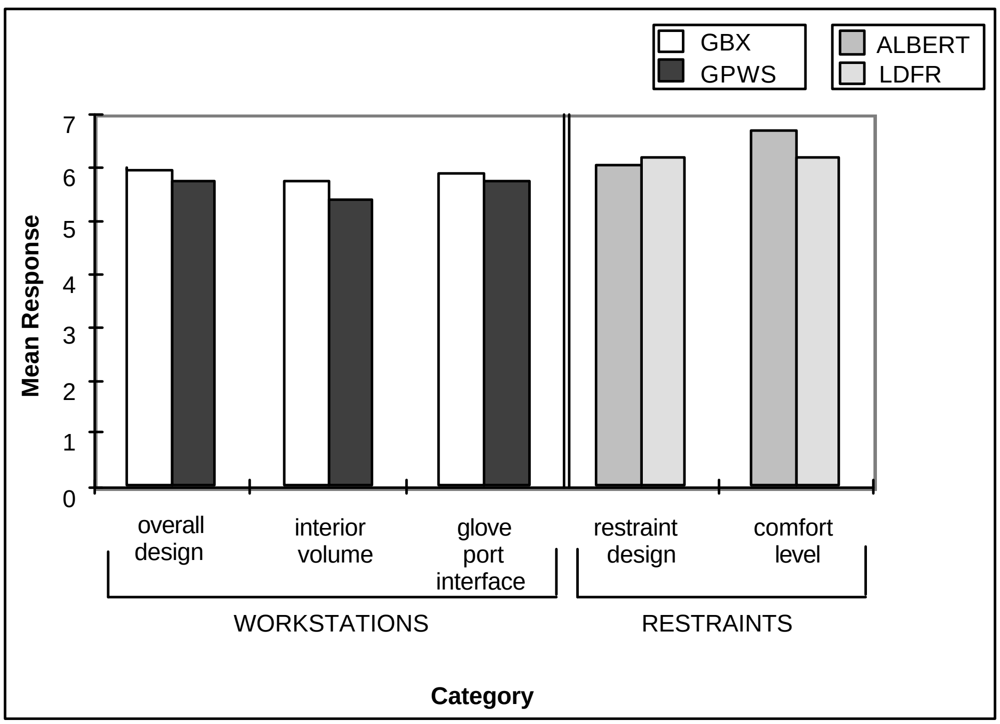

Figure 9. Mean questionnaire responses.

It is interesting to note that the GBX rated higher on interior volume, even though its interior volume is less than one-quarter that of the GPWS. The explanation for this result may be found in question 10, which asked the subjects to rate the two workstations' interior volumes with respect to retrieving and securing loose items. The GBX received a mean rating of 5.6, and the GPWS received a 4.5. It is logical that retrieving and securing loose items was easier in the smaller of the two workstations, and this discrepancy explains the GBX's higher rating on interior volume.

This finding was further confirmed when the ratings of the two workstations were analyzed separately for the force/torque and assembly tasks. The ratings for the GBX and GPWS were 6 and 6.2 (respectively) for those subjects who performed the force/torque task, but 5.7 and 5.3 (respectively) for those subjects who performed the assembly task. As anticipated, the volume had more negative effect (lower scores) on ratings when the subjects were performing the assembly task. In addition, no noticeable difference in ratings was observed between the GBX and the GPWS during the force/torque task. However, the subjects who only performed the assembly task rated the GBX higher (better) than the GPWS. This finding was attributed to the fact that difficulty in retrieving loose items may have had more impact on their subjective preference than the clutter within the interior volume.

Another interesting result was the higher rating that the LDFR received for stability while applying force or torque. It was expected that ALBERT's unique knee support would cause subjects to rate it as a more stable lower body restraint. One subject's general comments reveal a possible explanation. This subject stated that the LDFR restrained the feet quite well, and the workstations, "effectively restrained...my forearm." For a 20-30 second period of microgravity, perhaps one may consider the arm restraint provided by the workstation a positive aid. Yet for extended periods of microgravity, such as eight-hour shifts on a Shuttle mission, it is crucial that one be adequately restrained at the lower body so that all the force and torque imparted by the upper body may be applied to the glovebox tasks and not to maintaining proper restraint. Also, as stated earlier, the slight unsturdiness of the ALBERT mockup may have impacted responses to this question.

Other subjects' general comments also revealed important workstation issues. While working at the GBX, one subject in the Force trial said that, "when I first did pull for almost [the] entire zero-g portion my entire arm and shoulder hurt." This subject went on to say that it was not surprising to learn that a crewmember experienced shoulder discomfort during extended GBX use. This subject's first pull trial occurred while using the LDFR at the GBX. No subjects complained of soreness while using the ALBERT at either workstation, and of course, the ALBERT was not present aboard STS-50.

Lastly, many subjects agreed that the ALBERT was the more comfortable restraint: "ALBERT was a better fit. Easier to achieve the desired fit," "ALBERT gave me more support...kept me more stable...ALBERT was more comfortable," and "possibly for long-term use [ALBERT] would be better."

4.0 SHUTTLE EVALUATIONS

The results of the previous GBX DSO 904, conducted onboard STS-50 served as the impetus for a second GBX DSO 904. As stated in Section 2.0, the STS-50 crewmembers rated the GBX design poorly and reported neck and shoulder pain. Such findings indicated that there were human factors issues which required further investigation. The DSO conducted onboard STS-73 provided a second opportunity to evaluate the GBX workstation and to manifest ALBERT as a possible aid to combat poor posture and its resultant discomfort. STS-73 carried the United States Microgravity Laboratory (USML)-2 into orbit on an almost 16-day mission.

The primary modification to the glovebox since STS-50 was an increase in volume. The modified glovebox extended out 3 inches more than the original glovebox flown on USML-1. In addition, the crewmembers did not use the rigid cuffs, so the arm movements were not as restricted as they were in the early design. Furthermore, the ALBERT restraint system was manifested as part of the DSO for use at this glovebox in order to provide knee support and to facilitate a natural microgravity posture.

4.1 Approach

The primary focus of the DSO-904 on STS-73 was threefold:

1) Assess postural differences for small and large subjects at the glovebox
2) Collect crew comments on the modified design
3) Investigate effects of foot restraint system with knee support on crew posture and comfort.

4.1.1 Subjects

Four crewmembers, two males and two females, participated in the experiment and represented a wide range of anthropometric percentiles. Two of them were the primary operators of the glovebox. The summary of their anthropometric data is given in Appendix G.

4.1.2 Equipment

The original ALBERT restraint attachment mechanism was modified so that it could be mounted to the handrails of the glovebox instead of mounting it to a flat panel surface. Overall design was identical to the KC-135 mockup, and the flight unit was certified to fly onboard the Spacelab.

A questionnaire was included in the Biomedical Checklist for the crew to complete during the mission (see Appendix H). The questionnaire consisted of four main categories:

(1) Glovebox operations
(2) Glovebox interior
(3) Restraint systems

(4) General comments on ALBERT

In addition, several blank videotapes, microcassettes and a microcassette player/recorder were manifested as part of the DSO hardware to give the crew options for the method of questionnaire completion.

4.1.3 Procedure

The preflight preparations included two crew familiarization sessions, Weightlessness Environment Training Facility (WETF) and KC-135 evaluations. The experiment consisted of subjective crew evaluations (to be collected in-flight and/or postflight) and postflight video analysis of posture at the glovebox. Following the mission, a postflight debrief was held with each crewmember to gather his/her comments on the glovebox and the ALBERT.

4.1.3.1 Preflight Briefings and Evaluations

Two sessions were held to familiarize the crewmembers with the experimental objectives and crew requirements and to demonstrate the ALBERT restraint system. A sample questionnaire was distributed and comments were compiled in terms of the applicability of the questions to glovebox operations.

Following the initial familiarization, a one-hour training session was arranged for the crewmembers to test ALBERT in the WETF and to practice with the adjustments in a simulated microgravity environment. Three crewmembers participated in this session. One crewmember conducted the actual evaluation, and two crewmembers observed the WETF run (see Figure 10).

As a follow-up, two of the crewmembers flew onboard the KC-135 to evaluate the ALBERT and to compare it to the current Spacelab restraint system (identical to the ISS Long Duration Foot Restraint (LDFR)). The crewmembers flew one day of the series of KC-135 flights described in Section 3.0. They were also asked to make the required adjustments in order to determine their most comfortable postures (see Figure 11).

See original document for graphics

Figure 10. A crewmember testing the ALBERT in the WETF

See original document for graphics

Figure 11. A crewmember testing the ALBERT onboard the KC-135.

4.1.3.2 In-flight/Postflight Crew Evaluations

Inflight crew requirements consisted of completing the questionnaire which addressed interface design issues for both the glovebox and ALBERT as well as perceived level of comfort. Completion of the questionnaire depended on the availability of the crewmember during the mission. If they could not complete the questionnaire in-flight, they were given the same questionnaire during postflight debriefs in order to capture their comments. In addition, these debriefs were conducted individually as structured interviews with each of the participating crewmembers.

Crewmembers were also required to videotape three one-hour sessions of the glovebox activities. These sessions were scheduled on flight day 2/18:30, flight day 7/21:45, and flight day 12/21:30. Each video segment had a number of interruptions due to loss of signal, blocked camera view, or change of camera field of view. During the timelined downlinks, video of both primary glovebox users was recorded. Inflight still photography of all four glovebox users was also collected. The primary users are shown in Figure 12.

Figure 12. Primary glovebox users at work.

4.1.3.3 Postflight Video Analysis

PVAT (Posture Video Analysis Tool), a tool developed by the HFEL (Whitmore and McKay, 1995), was used to identify the posture categories and to determine the mean percentage times the crew spent in these posture categories using the available video footage. The seven posture categories were: nominal/free-floating nominal, foot restrained, leg extension, extended reach, “hunched” shoulders, squat and body twist (see Figure 13). These categories were determined by a preliminary review of glovebox operations and by the potential physical discomfort that these operations may cause in different parts of the body. For example, the "hunched" shoulder posture was anticipated to cause discomfort or possible pain in the neck/shoulder region when assumed for extended periods of time. The video review process consisted of time-tagging each posture category observed on the video. Following the video analysis, the mean percentage time spent in each posture category was calculated.

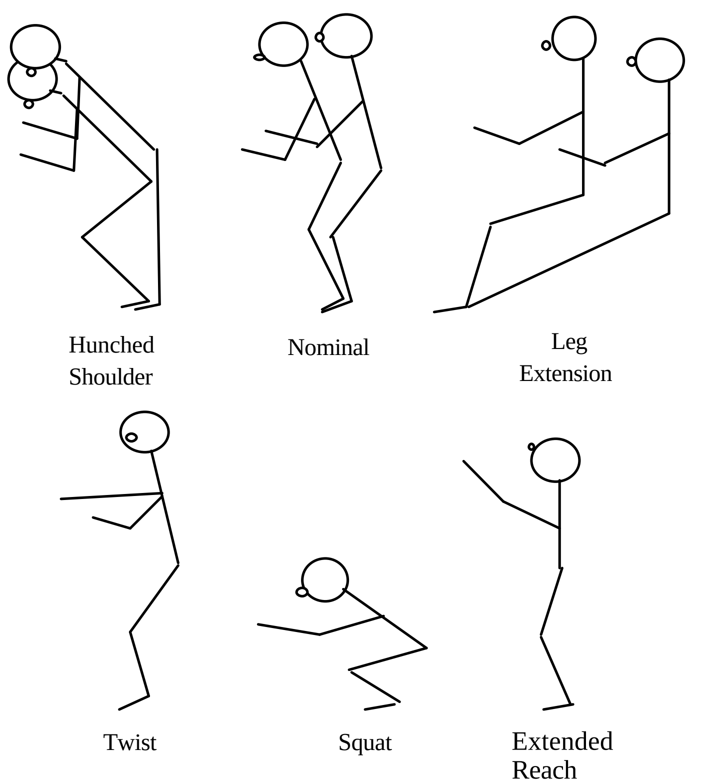

Figure 13. Posture categories used during video analysis.

4.2 Results and Conclusions

The modified glovebox with a large interior volume and without rigid cuffs was evaluated when the crew was using the ALBERT restraint system. The primary questions that were addressed in this evaluation were:

1) Does the posture differ for small and large subjects at different configurations?
2) Did the ALBERT with knee support facilitate a comfortable working posture?
3) Did the crew experience any discomfort working at the glovebox?

Four payload crewmembers participated in the study at different phases in order to address the above questions. The level of their involvement is summarized in

Table 6. The findings of the preflight, in-flight and postflight crew evaluations as well as the video analysis of posture data will be discussed separately in the following sections.

TABLE 6. Crew Participation during All Phases

Crew (Gender)	Level of Use	Pre-Flight Experience	Comments and Questionnaires	Video Data
1 (F)	Primary	• WETF Evaluation • DSO Briefing	In-Flight: comments on microcassette and videocassette Post-Flight: debrief only	√
2 (M)	Primary	• KC-135 Evaluation • WETF Observer • DSO Briefing	Post-Flight: debrief only	√
3 (M)	Secondary	• DSO Briefing only	Post-Flight: debrief and questionnaire	
4 (F)	Minimal	• KC-135 Evaluation • WETF Observer • DSO Briefing	Post-Flight: debrief and questionnaire	

4.2.1 Preflight WETF and KC-135 Evaluations

The tallest crewmember (S2), was concerned before the mission that the ALBERT may position him too close to the glovebox and that it may not facilitate a comfortable posture for him since it may not accommodate his stature. In an attempt to address this issue and to find the correct and comfortable adjustments for the crewmembers, a one-hour WETF session and one KC-135 flight were completed. As an outcome of these evaluations, the crewmembers determined their best ALBERT setup. The tall crewmember (S2) reported that the ALBERT did provide a comfortable posture and that his initial concern was not an issue.

4.2.2 In-flight/Postflight Crew Evaluations

Overall, the modified GBX design received more positive comments than the original design. The crewmembers indicated that not using the cuffs and leaving the doors off offered a wider range of arm movements. No fatigue was reported. The only item that might require some modification was found to be interior illumination, which was consistent with the previous findings.

All the crewmembers recommended ALBERT for use in future missions. They appeared to find a comfortable position for themselves. Even though the locking mechanism was not tight enough for tasks that either required fine manipulation or force, it appeared to be an advantage for a multi-tasking environment, where the operator needed to switch between working in the glovebox and reading the microscope above the glovebox. When needed, the loose lock mechanism actually provided some flexibility for the crewmember so that he or she could easily reconfigure ALBERT to accommodate the new posture. One crewmember suggested that the lock mechanism be modified such that it would provide the option to lock it tight or to leave it loose depending on the task requirements. Overall, the ALBERT restraint system was rated acceptable. It was easy to adjust and comfortable to use. Crew ratings and comments on the glovebox and ALBERT are provided in Appendix I.

4.2.3 Postflight Video Analysis

The posture evaluations of the two crewmembers revealed that both the short and the tall crewmember assumed "hunched shoulder" most of the time when compared to the other posture categories (see Figure 14). However, it was interesting to note that the tall crewmember (S2) spent more time in this posture than the short crewmember (S1). This result was inconsistent with the KC-135 evaluations where both the tall and the short subjects had similar percentages. The inconsistency was partly attributed to the fact that the KC-135 flights consisted of very short microgravity segments. The task performed on the KC-135 lasted less than 20 seconds and did not require fine manipulation and close-up monitoring. In contrast, the glovebox tasks onboard the Shuttle required fine manipulation, and low illumination levels inside the glovebox resulted in a need to get very close to the viewing window. Therefore, the tasks forced the crewmember to assume a "hunched shoulder" posture. As a result, the tall crewmember was in "hunched shoulder" more than the short crewmember. The fact that no discomfort was reported on this mission strengthens the previous finding that providing a more flexible glove port interface for the arms reduced the possibility of experiencing any discomfort.

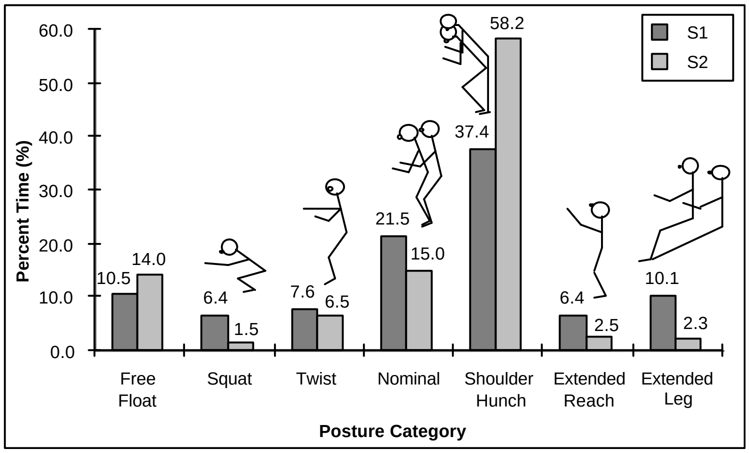

Figure 14. Percentage of time primary crewmembers spent in each posture category.

5.0 DISCUSSION

These Shuttle and KC-135 studies discussed in Sections 3.0 and 4.0 were preliminary investigations with a relatively narrow scope (see Figure 15). More in-depth studies are being planned to further investigate the effects of different workstation/restraint configurations on the following variables: posture, the ability to produce force and torque, muscle fatigue, and fine motor skills. Also, due to a lack of time and resources on both the KC-135 and the Orbiter, some data sets were incomplete.

Yet enough data was collected to learn that not all workstation/restraint configurations generate similar effects on performance. Some combinations have a synergistic effect; for example, during the KC-135 phase of experimentation, subjects imparted the greatest force for the push task at the GBX/ALBERT configuration. On the other hand, the lowest force for the pull task was seen at this configuration also.

The additional knee support in combination with flexible or large arm holes appeared to facilitate a comfortable posture even though it might not be the optimum microgravity posture. The ALBERT provided flexibility to the operator to change postures without egressing the restraint. It appears that the task requirement (i.e., close-up monitoring of the GBX interior) was the primary cause of the "hunched shoulder" posture. The fixed work surface height (see Table 2) may have had an additional effect on posture. Even though both the ALBERT and the LDFR had height adjustability, the glovebox work surface was too low for a tall operator and therefore did not allow for correct/optimal height adjustment. The workstation height should be a minimum of 46.8 in (118.9 cm). At that height, a 95th percentile American male is able to work comfortably, and small operators may adjust the height of the foot restraint to bring them into a comfortable working posture (Whitmore et al., 1995).

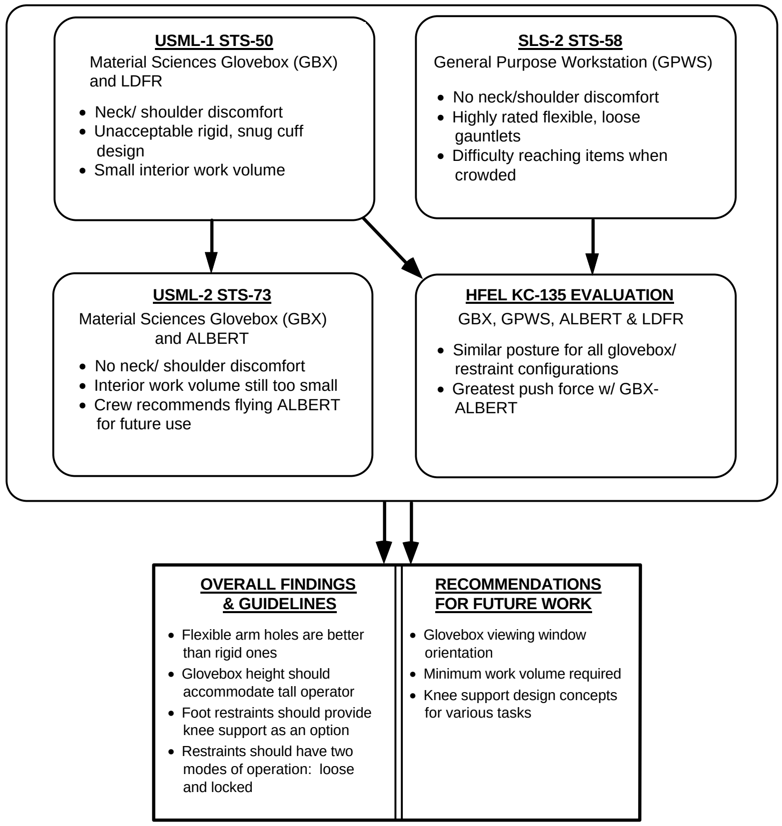

Figure 15. Summary of glovebox evaluations.

There was one inconsistent finding between the two studies; the working postures for short female and tall male subjects were very similar on the KC-135, while they were different onboard the shuttle. This difference was attributed to the task requirements and to the difference in microgravity duration. The KC-135 tasks did not require close-up monitoring, whereas the shuttle glovebox tasks did. Moreover, each microgravity parabola lasted approximately 20-30 seconds during the KC-135 flights, and the glovebox operations on the Shuttle lasted throughout the 8-hour shift. Both the force/torque and the assembly tasks were therefore designed either to be completed within 20 seconds or in 20-second increments. In contrast, there were no time constraints on microgravity in the Shuttle environment.

The findings of this study were clearly task dependent, and future studies need to expand and to focus on task-independent evaluations with objective performance measures in order to quantify various design effects.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Evaluations of various glovebox/restraints configurations led to the development of preliminary design guidelines for glovebox-type workstations and foot restraints:

Preliminary glovebox guidelines:

1) Provide flexible arm holes (instead of rigid) to allow maximum range of arm movement for repetitive fine motor tasks
2) Height of the glovebox should be designed for a 95 percentile American male
3) Provide height-adjustable foot restraints in order to accommodate wide range of users

Preliminary foot restraint guidelines:

1) Provide knee support when task requires force applications
2) Provide two mechanical modes: loose (for non-egress adjustment) and lock-down (to keep the restraint position fixed and rigid)
3) Number of adjustments should not exceed 5 operations while providing height, in-out and orientation adjustability
4) Provide simple adjustment mechanism operation to encourage the user to find his/her best fit

Moreover, there are a number of issues which also require investigation so that they may also be addressed in the guidelines.

Glovebox:

1) Orientation of viewing window relative to the arm holes
2) Minimum work volume in an enclosed work area
3) Arm hole design for force/torque tasks

Foot restraint:

1) Various knee support designs to accommodate a variety of forces
2) Accommodation of a 95th percentile American male

Comprehensive future studies onboard the KC-135 and Shuttle will result in a better understanding of design effects and in the quantification of their impact on performance. The findings will contribute to the refinement of design guidelines which, in turn, will support efforts both to design better gloveboxes and to select optimum, accompanying foot restraints given the workstation and task requirements.

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Appendix A

Anthropometric Measurements of the KC-135 Subjects

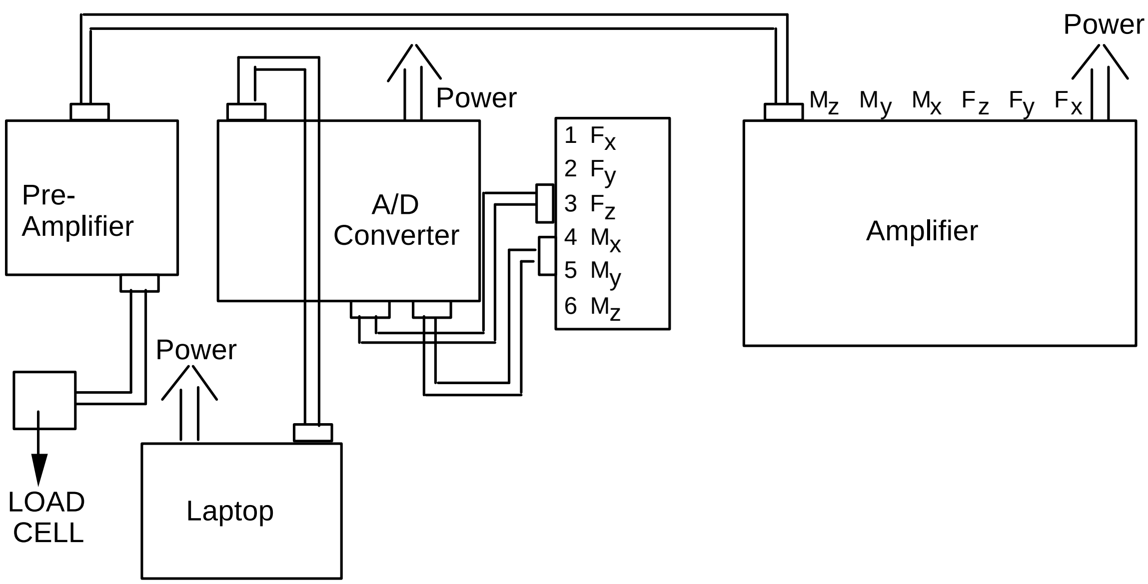
TABLE A-1. Anthropometric Measurements of the KC-135 Subjects

Anthropometric Measurement*	MINIMUM Male	MINIMUM Female	MAXIMUM Male	MAXIMUM Female	MEAN VALUE Male	MEAN VALUE Female
Stature	67.4 (171.3)	59.4 (151.0)	72.3 (183.7)	68.9 (175.0)	69.9 (177.5)	64.1 (163.0)
Shoulder Height	56.1 (142.4)	48.3 (122.7)	60.2 (153.0)	57.5 (146.1)	58.1 (147.7)	52.9 (134.4)
Elbow Height	43.2 (109.8)	37.7 (95.7)	46.9 (119.1)	43.0 (109.1)	45.1 (114.5)	40.3 (102.4)
Arm reach from the wall	32.2 (81.8)	28.9 (73.5)	35.2 (89.5)	33.9 (86.1)	33.7 (85.7)	31.4 (79.8)
Shoulder Breadth-bideltoid	16.4 (41.7)	13.9 (35.3)	17.2 (43.6)	15.0 (38.1)	16.8 (42.7)	14.4 (36.7)
Forearm-hand length	18.6 (47.2)	15.6 (39.6)	19.9 (50.6)	18.7 (47.4)	19.3 (48.9)	17.1 (43.5)
Shoulder-elbow length	13.3 (33.7)	12.3 (31.2)	15.6 (39.5)	15.2 (38.5)	14.4 (36.6)	13.7 (34.9)
Biceps circumference	11.6 (29.4)	8.30 (21.1)	12.8 (32.5)	11.5 (29.3)	12.2 (31.0)	9.90 (25.2)
Forearm circumference	11.0 (28.0)	8.50 (21.6)	11.2 (28.4)	8.80 (22.3)	11.1 (28.2)	8.70 (22.0)
Maximum Grip Strength, lb (kg) (at 90° elbow flexion)	116.8 (53.0)	63.9 (29.0)	154.3 (70.0)	77.2 (35.0)	135.6 (61.5)	70.5 (32.0)
Maximum Arm Torque, ft-lb (N-m) (at 90° elbow flexion)	5.17 (7.005)	1.92 (2.60)	5.18 (7.02)	2.73 (3.70)	5.17 (7.01)	2.36 (3.20)
Maximum Arm Force: Pull, lb (N) (at 90° elbow flexion)	30.7 (137.4)	24.07 (107.9)	82.1 (368.2)	32.9 (147.4)	56.4 (252.8)	28.5 (127.7)
Maximum Arm Force: Push, lb (N) (at 90° elbow flexion)	78.4 (351.2)	17.9 (80.2)	78.4 (351.2)	27.7 (124.2)	78.4 (351.2)	22.8 (102.2)
Mean Power Frequency: Pull, Hz, Posterior Deltoid (Pectoralis) S1 only	62 (68)		72 (92)		67.8 (78.3)	
Mean Power Frequency: Push, Hz, Posterior Deltoid (Pectoralis) S1 only	66 (65)		78 (71)		73.3 (67.9)	
Mean Power Frequency: Rotate, Hz, Posterior Deltoid (Pectoralis) S1 only	72 (47)		83 (82)		76.4 (71.0)	

*in inches (measurements in centimeters appear in parentheses), unless otherwise noted

Appendix B

Load Cell Force/Torque Data Acquisition System Hardware Sketch



Appendix C

Postflight Questionnaire

Questionnaire - KC-135

Ergonomic Evaluation of Glovebox and Restraint Configurations

1	2	3	4	5	6	7
Completely Unacceptable			Borderline			Completely Acceptable

GLOVEBOX (GBX) OPERATIONS

For the following questions, provide a separate response for the GPWS and the Material Sciences (Mat. Sci.) GBX.

A. Acceptability of both GBXs in terms of:

1. Performing the task
2. Handling task hardware
3. ~~Monitoring digital readout of your strength~~ *(NOTE: digital readout not used)*
4. Illumination inside GBX
5. Level of reflection or glare off viewing windows
6. GBX height
7. Location /Orientation of viewing window

GLOVEBOX INTERIOR:

B. Acceptability of both GBXs' interior volumes with respect to:

8. Accessing task hardware
9. Remaining work volume
10. Retrieving/Securing loose items (if any)

Questions 11-14 refer to a single GBX design.

C. Acceptability of GPWS in terms of:

11. Gauntlet height for your size
12. Getting in/out of gauntlets

D. Acceptability of Mat. Sci. GBX in terms of:

13. Distance between glove ports for your size
14. Getting in/out of glove ports

|___________|___________|____________|___________|___________|__________|
1 2 3 4 5 6 7

1	2	3	4	5	6	7
Completely Unacceptable			**Borderline**			**Completely Acceptable**

RESTRAINT SYSTEMS:

For the following questions, provide a separate response for ALBERT and for the LDFR.

E. Restraint's ability to support:

15. Maximum reach
16. Easy ingress/egress
17. Comfortable body posture
18. Stability while applying force/torque
19. Distance from GBX
20. Optimal performance of task

F. Comfort level and fit:

21. Lower back
22. Waist
23. Thigh
24. Shank
25. Feet

G. Restraint's usability in terms of:

26. Field of view (through GBX window)
27. Reach envelope

H. General:

28. Comment on the two restraints in terms of how well they supported you while performing the tasks, any discomfort you experienced, etc.

ANSWER SHEET

|__________|__________|__________|__________|__________|__________|

1	2	3	4	5	6	7
Completely Unacceptable			**Borderline**			**Completely Acceptable**

GBX QUESTIONS:

	GPWS	Mat. Sci.
1.	______	______
2.	______	______
3.	______	______
4.	______	______
5.	______	______
6.	______	______
7.	______	______
8.	______	______
9.	______	______
10.	______	______

11. ______
12. ______
13. ______
14. ______

RESTRAINT QUESTIONS:

	ALBERT	LDFR
15.	______	______
16.	______	______
17.	______	______
18.	______	______
19.	______	______
20.	______	______
21.	______	______

	ALBERT	LDFR
22.	______	______
23.	______	______
24.	______	______
25.	______	______
26.	______	______
27.	______	______

28. ____

____

GENERAL COMMENTS:

____

____

____

____

Appendix D

Assembly Task Inflight Procedures

See original document for graphics

Figure D-1. Assembly task inflight procedures.

Appendix E

Neutral Body Posture Diagram

See original document for graphics

Figure E-1. Neutral body posture diagram.

Appendix F

EMG Results for Subject 1

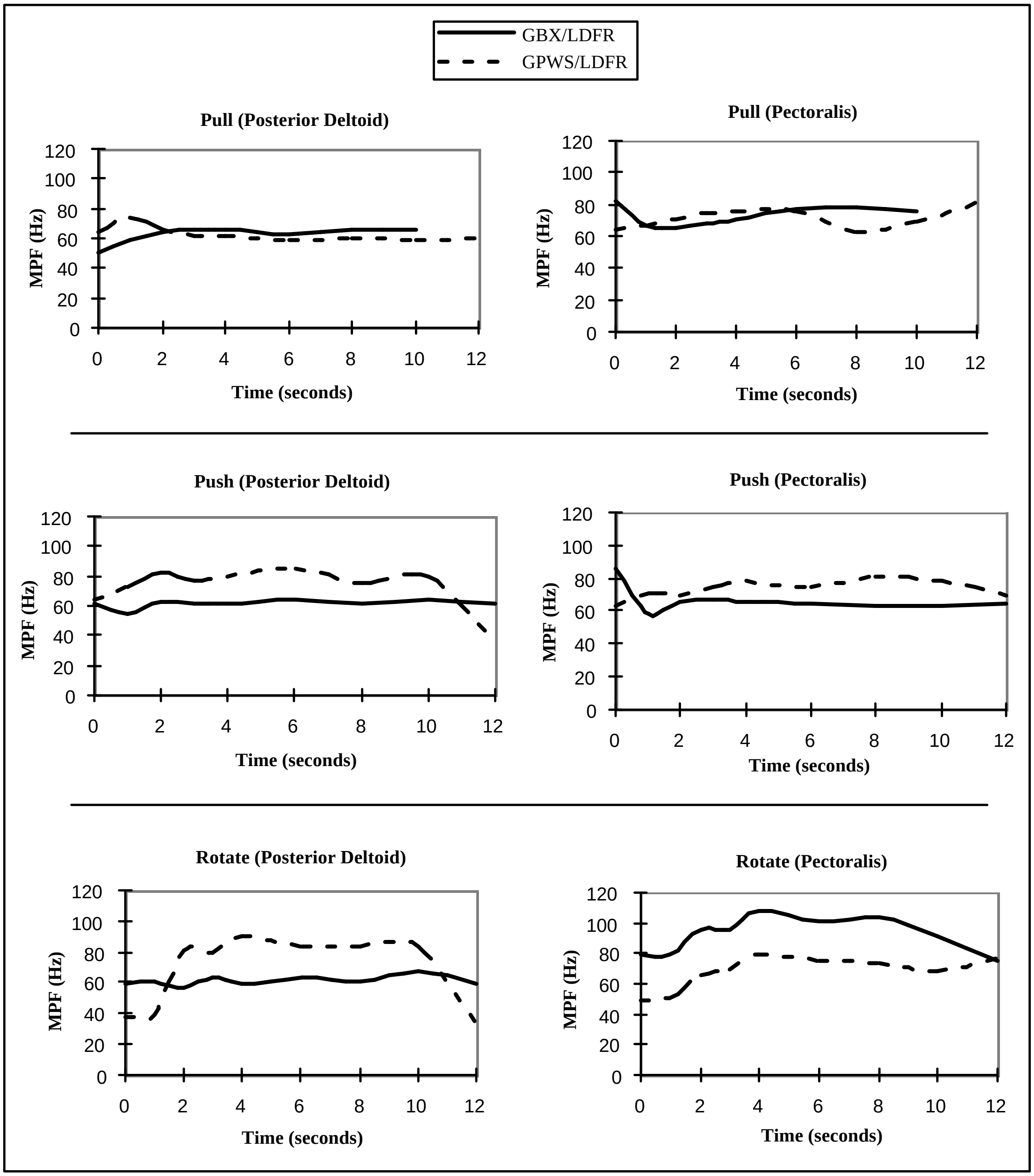


Figure F-1. EMG results for subject 1.

Appendix G

Summary of Crew Anthropometric Data

TABLE G-1. Summary of Crew Anthropometric Data†

Anthropometric Measurement*†	**S1**	**S2**	**S4**
Stature	64.1 (162.9)	70.9 (180.1)	64.1 (162.7)
Arm reach from the wall	28.9 (73.5)	35.0 (88.8)	29.6 (75.2)
Shoulder Breadth-bideltoid	14.7 (37.4)	17.8 (45.1)	15.7 (39.8)
Forearm-hand length	16.5 (41.9)	19.9 (50.6)	16.5 (42.0)
Shoulder-elbow length	13.1 (33.2)	14.8 (37.7)	13.0 (32.9)

*in inches (measurements in centimeters appear in parentheses)
† measurements for S3 were not available.

Appendix H

DSO 904 Questionnaire

Questionnaire - DSO 904

Ergonomic Evaluation of Glovebox and Restraint Configurations

1	2	3	4	5	6	7
Completely Unacceptable			**Borderline**			**Completely Acceptable**

GLOVEBOX (GBX) OPERATIONS

A. Acceptability of GBX in terms of:

1. Performing the experiment
2. Loading/Unloading the GBX
3. GBX camera adjustments
4. Handling experiment hardware
5. Monitoring Color TV Monitor view of experiment
6. Assembling/Disassembling the GBX hardware
7. Attaching/Detaching gloves
8. Cleaning interior work space
9. Using auxiliary cleanup devices (vacuum, swabs, etc.)
10. Noise level at workstation
11. Illumination inside GBX
12. Level of reflection or glare off viewing windows
13. Labeling and packaging of experiment hardware
14. GBX height
15. Distance between glove ports for your size
16. GBX microscope location
17. Location /Orientation of viewing window
18. Visibility/Accessibility of GBX control panel
19. Getting in/out of glove ports
20. Temporary stowage provision
21. Adequacy of restraints for holding equipment, tissues, supplies, vials, etc.
22. Adequacy of procedures
23. Location of the procedures

GLOVEBOX INTERIOR:

B. Acceptability of GBX interior volume with respect to:

24. Accessing stowed items
25. Location/Accessibility of temporary stowage
26. Remaining work volume after complete setup of experiment
27. Retrieving/Securing loose items

RESTRAINT SYSTEMS:

28. How many different restraints did you use while working at the GBX (1,2, or 3)? Which ones? Label them 1, 2, and 3.

For the following questions, provide a separate response for each restraint used.

C. Restraint's ability to support:

29. Maximum reach
30. Easy ingress/egress
31. Comfortable body posture
32. Stability while applying force/torque
33. Distance from GBX
34. Optimal performance of task

D. Comfort level and fit:

35. Lower back
36. Waist
37. Thigh
38. Shank
39. Feet
40. Note longest uninterrupted work period with each restraint

E. Restraint's usability in terms of:

41. Field of view (window)
42. Field of view (Color TV Monitor)
43. Reach to switches at control panel
44. Interference with other USML-2 activities

F. Adjustability (mechanism) at:

45. Handrail attachment point - Rotation
46. "Knee" joint - Rotation
47. "Knee" joint - Location
48. "Foot" joint - Rotation
49. "Foot" joint - Location

G. General questions:

50. Ease of adjustment while in it
51. Assembly/Disassembly
52. Stow/Destow
53. Temporary Stow/Destow while not using
54. Please compare ALBERT to other restraints used (based on past experience if only used ALBERT at the GBX).
55. Please comment on ALBERT's latch mechanism, knobs, or fasteners used; sturdiness of the adjustment joints; any need for a second operator for adjustments while in it.

ANSWER SHEET

1	2	3	4	5	6	7
Completely Unacceptable			**Borderline**			**Completely Acceptable**

1. ______	10. ______	19. ______
2. ______	11. ______	20. ______
3. ______	12. ______	21. ______
4. ______	13. ______	22. ______
5. ______	14. ______	23. ______
6. ______	15. ______	24. ______
7. ______	16. ______	25. ______
8. ______	17. ______	26. ______
9. ______	18. ______	27. ______

28. ____

____

	Rstrnt. 1	Rstrnt. 2	Rstrnt. 3		Rstrnt. 1	Rstrnt. 2	Rstrnt. 3
29.	______	______	______	42.	______	______	______
30.	______	______	______	43.	______	______	______
31.	______	______	______	44.	______	______	______
32.	______	______	______	45.	______	______	______
33.	______	______	______	46.	______	______	______
34.	______	______	______	47.	______	______	______
35.	______	______	______	48.	______	______	______
36.	______	______	______	49.	______	______	______
37.	______	______	______	50.	______	______	______
38.	______	______	______	51.	______	______	______
39.	______	______	______	52.	______	______	______
40.	______	______	______	53.	______	______	______
41.	______	______	______				

54. ____

55. ____

GENERAL COMMENTS:

____

____

Appendix I

Crew Questionnaire Ratings and Comments

Table I-1. Crew Comments and Ratings during Debriefs

Description	3	2	1	Crew Comments (3=Acceptable; 2=Borderline; 1=Unacceptable)
Glovebox Issues				
Loading/Unloading		√		S1: Had to think a lot about where things were going to go and had a grid installed inside
Temp. stowage provision- GBX interior	√			S1: Magnets & Velcro were very helpful - need at least 1 of the 2 inside the GBX S2: Magnets were good for small pieces and were very important; Velcro inside was used for everything
Temp. stowage provision- Outside of GBX	√			S2: Everything was stowed on back wall of Spacelab with Velcro S4: Lots of Velcro in close proximity
Work volume inside GBX		√		S1: Can always be bigger but OK for what we were doing; S4: We shoved too much inside, but it was workable S3: Would be nice if it were larger; some things got in the way at times S2: Volume was adequate - not having the doors on increased the range of motion in the GBX tremendously
Handling hardware		√		S3: Quite often cables got in the way of equipment that needed to be moved around as part of the experiment
Workstation Issues				
Noise	√			S1: Noticed noise most when you shut off equipment and realized the quiet; S2: Tuned it out easily S3: When high data rate recorder was high-speed rewinding, it sounded like a buzzsaw, but that didn't last long
Illumination			√	S2: Light level inside GBX was low so I had to hunch over the GBX most of the time to see inside
ALBERT - Posture Issues				
General fatigue	√			S1: No discomfort that I can say was definitely a result of ALBERT use S4: No fatigue; no discomfort using ALBERT; S3: No fatigue; no discomfort
Stability		√		S1: For fine work, stabilized by pushing feet together against center beam or by keeping rest of my body flexed -
Feet		√		S1: Takes effort to keep feet in - need to flex feet to stay stable
Back		√		S1: Back discomfort was worse during days in the GBX, but my posture in general isn't good
Optimal task performance	√			S1: Would loop feet around knee part when up at microscope; twined feet around it to get at lockers above GBX and for quickie tasks like turning cranks above GBX
Comfortable body posture	√-			S1: Had a hard time finding a favorite position; liked my feet back in the WETF but straight down on-orbit S4: Didn't have to set it up that precisely; just "hopped on" without making adjustments specifically for me

Description	3	2	1	Crew Comments (3=Acceptable; 2=Borderline; 1=Unacceptable)
				S3: Used it like a parrot on a perch; never locked my toes into the lower part - wrapped them around center beam
				S2: Hooked feet under foot part instead of inside it; never thought about posture - was always comfortable
Adjustment while in ALB	√			S4: I liked that the knee joint didn't lock; when I wanted it to adjust it I could just do it be moving my feet
				S3: I could reposition myself by kicking ALBERT into a new position while still in it
Distance from GBX				S1: Wanted to be closer and still be snugly in ALBERT, but there wouldn't be clearance for my knees anyway
ALBERT - Hardware Issues				
"Knee" joint		√		S1: Needs to be made very, very tight more easily - needed help to get it tight enough to stay put
				S4: For someone who needs positive restraint, it needs to be a lot tighter
				S3: If I pushed or pulled on it, it moved; it didn't really offer any resistance; needs to lock down a little better
Knobs	√			S1: Very nice and screwed on hard; they're not going to move once in place
				S3: Took only seconds to adjust; loosen, adjust, and tighten, then I could just forget about it
Assembly	√			S1: Really easy to put together
Adjustment range		√		S1: Wanted to always have knee pads very close to backs of knees and that wasn't possible
				S3: Lots of latitude for comfort; only adjusted it once or twice to move it out farther from the GBX for himself
Compare to other restraint				S1: Used LDFR for an hour; not really happy with it; rather be curled up in ALBERT
				S3: Preferred foot loops for precise, fine work; made "fist" with toes to lock down and braced arms against GBX
				S2: LDFR was comfortable but not as comfortable as ALBERT
Recommend it for future?				All four crewmembers highly recommend flying ALBERT for future GBX work

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
July 1996

3. REPORT TYPE AND DATES COVERED
NASA Contractor Report

4. TITLE AND SUBTITLE
Ergonomic Evaluations of Microgravity Workstations

5. FUNDING NUMBERS

6. AUTHOR(S)
Mihriban Whitmore*, Andrea Berman*, Diane Byerly

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lyndon B. Johnson Space Center
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
CR-1996-201378

11. SUPPLEMENTARY NOTES
* Lockheed Martin Engineering and Sciences Company
Houston, Texas

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Available from the NASA Center for AeroSpace Information (CASI)
7121 Standard
Hanover, MD 21076-1320

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Various gloveboxes (GBXs) have been used aboard the Shuttle and ISS. Though the overall technical specifications are similar, each GBX's crew interface is unique. JSC conducted a series of ergonomic evaluations of the various glovebox designs to identify human factors requirements for new designs to provide operator commonality across different designs. We conducted 2 0g evaluations aboard the Shuttle to evaluate the material sciences GBX and the General Purpose Workstation (GPWS), and a KC-135 evaluation to compare combinations of arm hole interfaces and foot restraints (flexible arm holes were better than rigid ports for repetitive fine manipulation tasks). Posture analysis revealed that the smallest and tallest subjects assumed similar postures at all four configurations, suggesting that problematic postures are not necessarily a function of the operator's height but a function of the task characteristics. There was concern that the subjects were using the restrictive nature of the GBX's cuffs as an upper-body restraint to achieve such high forces, which might lead to neck/shoulder discomfort. EMG data revealed more consistent muscle performance at the GBX; the variability in the EMG profiles observed at the GPWS was attributed to the subjects' attempts to provide more stabilization for themselves in the loose, flexible gauntlets. Tests revealed that the GBX should be designed for a 95 percentile American male to accommodate a neutral working posture. In addition, the foot restraint with knee support appeared beneficial for GBX operations. Crew comments were to provide 2 foot restraint mechanical modes, loose and lock-down, to accommodate a wide range of tasks without egressing the restraint system. Thus far, we have developed preliminary design guidelines for GBXs and foot

14. SUBJECT TERMS

glovebox, foot restraint, microgravity, posture, restraint, interfaces

15. NUMBER OF PAGES
57

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

Standard Form 298 (Rev Feb 89) (MS Word Mar 97)
Prescribed by ANSI Std. 239-18
298-102

NSN 7540-01-280-5500